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HYDROGEN SAFETY

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Annual Report for the Period
January 1 to December 31, 1966

(Progress Report No. 12)

BUREAU OF MINES, PITTSBURGH, PA.

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Pittsburgh, Pennsylvania

HYDROGEN SAFETY

Annual Report for the Period
January 1 to December 31, 1966

(Progress Report No. 12)

by

A. Strasser
E. L. Litchfield
J. Grumer

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for
Space Nuclear Propulsion Office
Cleveland Extension
January 1967

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INTRODUCTION

This is the third annual report and twelfth quarterly progress report on a hydrogen safety program covering (a) review of existing practices, (b) delineation of areas in which new information needs to be developed, and (c) compilation of a safety summary that will be broadly applicable to operations involving hydrogen.

During the report period (January 1 to December 31, 1966) the theoretical study of hydrogen plumes was continued and the plume problem was studied experimentally, using helium plumes. A draft of the safety summary entitled "Principles of Safe Handling of Liquid Hydrogen" was submitted for review. Hydrogen plume theory was applied in predicting conditions under which large flows of hydrogen may be disposed of by venting (no burning) and in determining when flaring is necessary; disposal by burning over water (burn pond) was also given some consideration. A study to determine the proportion of oxygen in the concentrate produced by contact of air with liquid hydrogen showed that significant oxygen enrichment may occur in the liquefaction process.

PROGRESS DURING YEAR

<u>General Hydrogen Safety Studies</u> (A. Strasser, S. R. Harris, P. M. Gussey, and J. Grumer)

Staff members discussed hydrogen safety matters with representatives of industrial contractors and federal agencies. These discussions included a requested review of two proposed facilities at Wright-Patterson Air Force Base (WPAFB). At one of these facilities, it will be necessary to dispose of about 0.35 lbs/sec of gaseous hydrogen. WPAFB is considering burning the hydrogen over a water pond. Information was provided them on the alternative possibility of using flare stacks. Instability in flare stack operation due to very low flows of hydrogen or the use of coupled twin stacks were considered in this connection. Flare stacks and burn ponds were compared with respect to flame radiation and flame height. Information gained at Aerojet-Sacramento and NRDS, Nevada was useful in these discussions. At the other facility, components of hypersonic vehicles fueled with liquid hydrogen will

be tested during runs involving up to 7,000 gallons of liquid hydrogen. Safety features of this facility were discussed with WPAFB.

Safety problems in connection with the operation of a 7500 gallon bubble chamber were discussed with personnel of the Argonne National Laboratory. Consideration was given to the characteristics of various hydrogen detectors and the conditions under which venting or flaring is preferable as a means of hydrogen disposal.

Hydrogen safety problems in connection with a 50 megawatt boiling water reactor being constructed at Idaho Falls for the Atomic Energy Commission were discussed. Concern exists about the possible production of large amounts of hydrogen should the core fail and water come in contact with zirconium-clad elements.

Assistance was given in investigating explosions of hydrogen vent line-flare stack systems. Certain theoretical considerations were applied in an attempt to explain these incidents which seem to have occurred when the flow of hydrogen was low.

Low Flow Stability Limits of Hydrogen Flames on Flare Stacks

Experience shows that air and hydrogen may mix in a flare stack or piping when the hydrogen flow is low. Classical flashback theory does not seem relevant to this problem.[1/] In using either the classical[2,3/] or empirical[4/] flashback equations to determine flashback limits, it is necessary to specify the relative amounts of hydrogen and air in the mixture. This may be chosen for example to correspond to the rich limit of flammability (74 percent hydrogen) or to the peak flashback limit (36 percent hydrogen). The results are given in table 1. These limits were calculated for two

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1/ Hydrogen Safety Progress Report No. 9 for the period January 1 to March 31, 1966.

2/ Lewis, B. and G. von Elbe. Stability and Structure of Burner Flames, Jour. Chemical Phys., Vol. 11, 1943, pp. 75-97

3/ Grumer, J., M. E. Harris, V. R. Rowe. Fundamental Flashback, Blowoff, and Yellow-Tip Limits of Fuel Gas Air Mixtures. Bureau of Mines Report of Investigations 5225, 1956, 199 pp.

4/ Hajek, J. D. and E. E. Ludwig. How to Design a Safe Flare Stack. Petro. Chem. Eng., Vol. 32, pp. C31-C38, June 1960 and pp. C44-C51, July 1960.

Table 1. - Backfire Limits of Hydrogen Flare Stacks.

Flare Stack Diam. In.	Actual Hydrogen Flows, lb/sec		Predicted Hydrogen Flows, lb/sec				
	Fire in stack	No fire in stack	Classical Flashback Equation		Hajek & Ludwig equation[4]		Aerodynamic Instability Theory
			36% H_2 in air	74% H_2 in air	36% H_2 in air	74% H_2 in air	
Twin 8	0.10 to 0.35	0.4	0.11	0.028	4.8	0.28	0.26
18	7.5×10^{-5}	9.1×10^{-4} [a]	0.32	0.08	27	1.6	9.7×10^{-3}
42	-	4.9×10^{-3} [a]	>0.32	>0.08	>27	>1.6	0.12

a/ Manufacturer's specified minimum flow.

flare stacks and are generally in disagreement with calculations from flows at which fire, explosion or stable flame has been observed.

An alternative approach to predicting low flow stability limits of hydrogen flames on flare stacks was proposed,[1/] primarily as an explanation of backfire in a system where hydrogen was being flared through two 8 inch id flare stacks connected to a common manifold (Table 1, Twin 8). For flows between 0.1 to 0.35 lbs/sec of hydrogen, flame formed inside one of the flare stacks near the manifold and oscillated between the two stacks. Both flare stacks operated satisfactorily when the flow into the manifold was 0.4 lbs/sec. Experiments with helium showed that air can be inducted down one stack while buoyant gases are flowing up the other. Pitot tube measurements at the top of each flare stack gave negative readings for one stack and positive readings for the other. It is possible that air is drawn downward into the one stack by the buoyancy head of a column of hydrogen flowing upward in the other stack; resistance to the downward flow of air is caused by friction with the stack walls. (Frictional pressure due to hydrogen flow is neglected for simplicity). The frictional head for turbulent flow ΔP_α ft, and the buoyancy head ΔP_γ are given by equations (1) and (2), respectively.[5/]

$$(\Delta P_\alpha)_{air} = \left[16L\ \rho_{air}\ V^2_{air}/\pi^2 D^5_{air}\right] \left[0.0036 + 0.24(2/R_e)^{.35}_{air}\right] \quad (1)$$

$$(\Delta P_\gamma)_{H_2} = gL\ \rho_{air}\ (1-d_{H_2}) \quad (2)$$

Equating (1) and (2), one obtains equation (3) which gives the maximum flow of air (ft^3/sec) that can be inducted by the system:

$$V_{air} = \frac{\pi\left[g\ (1-d_{H_2})\right]^{1/2} D_{air}^{2.5}}{4\left[0.0036 + 0.24\ (2/R_e)_{air}^{.35}\right]^{1/2}} \quad (3)$$

5/ Von Elbe, G. and J.Grumer. Air Entrainment in Gas Burners, Ind. and Eng. Chem., v. 40, No. 6, June 1948, pp. 1123-1129.

(g = gravitational constant, ft/sec^2; d = specific gravity; D = burner diameter, ft; Re = Reynolds number and ρ = density, lbs/ft^3)

If now one assumes that air mixes with hydrogen in the flare stack carrying the hydrogen the resulting mixture may contain 74 percent hydrogen, that is, be flammable. Pilot flames on top of flare stacks may ignite this mixture and flame may propagate into the flare stack. After flame propagates down one stack, air induction down the second stack depends on the buoyancy of the combustion products flowing up the first one. Flame propagation into the flare stack is impossible at higher flows of hydrogen if complete mixing with the inducted air is assumed. Based on these assumptions it becomes possible to calculate a limiting flow of hydrogen above which flame would not penetrate into the flare stack. As shown in table 1, the predicted limit for flame stability on the 8 inch twin flare stack is 0.26 lbs/sec. Experience shows the limit to be less than 0.4 lbs/sec, and more than 0.10 or perhaps 0.35 lbs/sec. This agreement is encouraging.

Fire or explosion in an 18 inch id single flare stack has been observed while hydrogen was flowing at a rate of about 7×10^{-5} lbs/sec. The manufacturers specified minimum flow for this flare stack is 0.1 ft/sec or 9.1×10^{-4} lbs/sec. The computed limiting hydrogen flow is 9.6×10^{-3} lbs/sec. For a 42 inch flare stack, the manufacturer's minimum flow is also 0.1 ft/sec or 4.9×10^{-3} lbs/sec. (The manufacturer's minimum flow velocity is 0.1 ft/sec for a 10 inch stack too). Agreement is within about an order of magnitude for the 18 inch stack, but in excess of two orders of magnitude for the 42 inch stack. It would be valuable to determine experimentally whether the proposed theory is correct or whether the value of 0.1 ft/sec is in fact applicable to all wide stacks as the manufacturer appears to think. Experiments with large flare stacks are difficult to run but perhaps laboratory scale model experiments under consideration can resolve the disagreement shown in table 1 for single flare stacks.

Two additional assumptions were made in the course of the calculation for a single flare stack. Based on the earlier assumption that the hydrogen-air mixture contains 74 percent H_2, 74 percent of the cross section of the stack was assigned to the hydrogen flow and the remaining annulus of 26 percent was assigned to the counter-current air flow. The frictional pressure head due to the downward flow of air in the pipe was assumed to be equivalent to the frictional pressure head for a circular pipe with a radius equivalent to the hydraulic radius of the postulated annulus.

Burning Rate of Hydrogen Diffusion Flames

To calculate burning rates of hydrogen diffusion flames, the flame height and flame area of two large hydrogen diffusion flames (table 2) were estimated from color photographs. The flame area was approximated by assuming that it equalled the surface of revolution of two base-butted cones. Two boundaries of the photographed flame outline were taken, one that of the most intense white and the second that between the white and yellow. The burning rate was calculated by dividing the flow of hydrogen by the flame area; air flow was neglected. The best estimate was a burning rate of about one foot per second. This may be compared with the peak burning velocity of 9 feet per second of premixed hydrogen air flames. The high diffusional burning rate indicates that complete combustion of hydrogen is readily attainable in flare stack flames.

Table 2. - Burning Rates of Large Hydrogen Diffusion Flames

	Flame A	Flame B
Port diam., in.	31[1/]	25, 30
Hydrogen flow, lbs/sec	70	6.6
Hydrogen flow, ft^3/sec	12,500	1,180
Flame height, ft	275 to 330	62 to 63
Flame surface area, $ft^2 x10^{-3}$	8.27 to 27.1	0.715 to 1.22
Burning rate, ft/sec	0.5 to 1.5	1.0 to 1.7
Burning rate (lbs/sec, ft^2)$x10^3$	2.6 to 8.5	5.4 to 9.2

1/ Recently received information corrected the port diameter given previously in Progress Report No. 9, Table 2.

Hydrogen Plumes

The results of Morton[6/] were applied to the determination of plume parameters when hydrogen is released from an orifice into a quiescent atmosphere. A first series of computations was based on

Morton's solution of the nondimensional equations of conservation of mass, momentum and density deficiency. This solution involved evaluating of an integral of the form,

$$\int_1^V \frac{t^3}{(t^5-1)^{1/2}} \, dt \ ,$$

where V is a dimensionless parameter depending on velocity and t is a dummy variable. Since the denominator of the integrand vanishes at the lower limit we evaluated the integral in separate computations by assuming that the lower limit was greater than 1 by amounts equal to 10^{-6} and 10^{-9}. These calculations indicated that the integral is unstable at its lower limit and depends critically on the small increment. In connection with another project, Litchfield[7/] had also calculated plume parameters, using Morton's equations more directly and without recourse to this integral. To avoid mathematical singularity, subsequent calculations presented here are based on Litchfield's direct integration of Morton's differential equations.

Morton's analysis involves an entrainment constant α = velocity of fluid flowing into the plume/vertical velocity at axis. Morton assigned value of 0.082 to α for buoyant plumes from fires of cellulosic materials and stated that α would have to be determined empirically. In hydrogen plume parameters calculation in the present study α was arbitrarily taken as 0.05, 0.082 and 0.1. As α increased, the calculated hydrogen concentration decreased and the plume width increased. In an earlier study, α was estimated for the case of an air jet in free air. It was found[8/] that the air jet expands in air at a half angle of approximately 10°. The tangent of this half angle is the ratio of horizontal to vertical velocity, provided that air is entrained without any change in static pressure. Thus for a jet of air the entrainment constant would be the tangent of 10° or approximately α = .18. Other data obtained with helium flowing from a 4 inch pipe at an average initial velocity of about 12.2 ft/sec yield an angle of expansion of 16° or α = 0.29.[9/] If such values of α are appropriate for hydrogen,

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6/ Morton, B. R. Forced Plumes, Journal of Fluid Mechanics, vol. 5, January 1959, pp. 151-163.

7/ Litchfield, E. L., D. J. Cohen, and M. H. Hay. Hydrogen Penetration Studies, BuMines Progress Report No. 3, July 1 - August 31, 1966, Purchase Request CC-26114 and CC-26115, John F. Kennedy Space Center, NASA.

8/ Primary Air Entrainment Progress Report No. 11, August 1 - October 31, 1962, Contract 14-09-050-2056, American Gas Association.

9/ Air Flows Into Uncontrolled Fires, A. Strasser and J. Grumer. Final Report No. 3909, January 1964, Purchase Order S-35287-60- National Bureau of Standards.

present calculations overestimate hydrogen concentrations at a given plume height. The entrainment constants for hydrogen must be determined. One approach is to measure the plume parameters in the laboratory and compare these measurements with predictions of the theory based on assumed values of the entrainment constant. Figures 1 and 2 indicate the predicted plume characteristics for a hydrogen flow of 0.5 lbs/sec at an initial temperature of 550°R and issuing from a 4 inch pipe. Separate curves are shown for the three assumed values of α.

The use of Litchfield's solution has a significant effect on the plume concentration, width and axial velocity. For a flow of 0.5 lbs/sec of hydrogen from a 4 inch id pipe, the hydrogen concentration reaches the lower flammable limit (4 percent) at a height of about 40 feet when $\alpha = 0.1$ and about 80 feet when $\alpha = 0.05$ (see figures 1 and 2). The previous calculation[10/] for this case assumed that $\alpha = 0.082$. A height of about 10 feet was obtained for the 4 percent limit; the plume widths were greater than those obtained by the present mathematical procedure and the axial velocities were approximately the same. The plume width is taken to be the radial distance at which concentration falls to 1/e of the axial concentration. For an initial temperature of 150°R, plume heights and diameters at various concentrations are somewhat less than those predicted for hydrogen at 550°R; respective velocities are very much lower. The calculation for 150°R took into account the density of hydrogen at 150°R but no corrections were made for the warming of hydrogen by surrounding air. Such a correction would lead to a reduction of the differences in plumes resulting from the two initial temperatures (see table 3).

It is of interest to consider the plumes formed by high flows from large pipes, such as the plume from a 3 ft orifice at a hydrogen flow of 100 lbs/sec (Table 4). Figure 3 shows the predicted concentrations; the height at which the 4 percent concentration limit is reached is 370 to 700 ft for $\alpha = 0.1$ and $\alpha = 0.05$ respectively. This plume spreads at a half angle of about 10°. Its velocity decreases rapidly with distance from the orifice. For example, the velocity is down to about 1/3 of the velocity at the orifice at a height of 45 ft for $\alpha = 0.1$. The corresponding height is 90 ft for $\alpha = 0.05$.

Figure 4 shows how the axial velocity and concentration change with flow rate at a height of 50 feet above a 6 inch orifice. Table 5 gives the results of calculations of plume diameter as a function of flow rate. Up to about 0.5 lbs/sec there is an increase in concentration with increasing flow. Above this rate, the concentration approaches a constant value. Plume diameter shows a similar trend and axial velocity increases with increasing initial flow rate. These calculations indicate that at high flow rates momentum transfer from the jet to the surrounding atmosphere approaches a constant level of momentum conservation.

10/ Hydrogen Safety Progress Report No. 11 for the period July 1 to September 30, 1966.

When the orifice diameter is varied for a given flow rate, (figure 5) the concentration increases as the diameter increases. Thus, venting a given flow of hydrogen through a wide stack to reduce linear velocity may not be desirable from the practical standpoint. According to Morton[6] "the most rapid removal of plume fluid from the source is obtained ... by releasing the fluids slowly from a large aperture and giving it the maximum buoyancy" (least mixing with air), "the most rapid mixing of the effluent with its environment is obtained in the jet". In the disposal of large flows of hydrogen, rapid removal of fluid from the neighborhood of the source with little mixing may only transfer the hazard to another location. A much better arrangement is a high momentum jet-like plume, which entrains enough air to form a nonflammable mixture. As indicated in table 6 plume diameter is not sensitive to change in diameter of the orifice, except for the lower limit imposed on the diameter of the orifice for a given flow by the acceptable back pressure for the system. The Mach number of the hydrogen issuing from the orifice must also be considered.

The foregoing discussion hinges considerably on the evaluation of α. The best present estimate is $\alpha = 0.1$; this will be refined as data are collected. Thus far, laboratory work has been carried out with helium for safety reasons; confirmatory experiments with hydrogen are planned. Data obtained with helium are presented in figure 6. The curves predict concentration versus height for a 3/4" orifice and a flow of .00092 lbs/sec of helium and for $\alpha = 0.05$, 0.082, and 0.1. The graph also shows averages of measured concentrations at 1, 2, 3 and 4 feet. The vertical lines at the averages include plus or minus one standard deviation for the respective average. The concentrations were measured in two ways. In one instance a 40 cc sample was collected from the plume with an evacuated tube in about 0.2 to 0.5 seconds. In the second instance sampling was carried out over a 5 minute interval by water displacement. There is considerable scatter in the experimental points as indicated by the rather large standard deviation. Attempts will be made to improve the reproducibility of the experiments. Duplicate analyses of samples indicate that the precision of the chromatographic helium analyses is 0.8 percent of the actual helium concentration. Two sample replicates show that the sampling error is at most 2.5 percent. Thus the total error in the sampling and analysis is no more than ±3.3 percent of the helium concentration. It appears that the greatest source of experimental uncertainty is due to variation of the plume itself. Movies of smoke-filled plumes show rapid fluctuations in plume shape. Measurement of velocity and comparison with theory will provide a semi-independent means of determining α (Velocity measurements depend on concentration measurements whether they are made with the density dependent pitot tube or the conductivity sensitive hot wire anemometer.) The entrainment coefficient is also being evaluated by other experimental procedures in a study concerned with hydrogen penetration through small openings.[7] Results from the two studies will be compared as soon as firm values of α are obtained by each.

Table 3. - Characteristics of Hydrogen Plumes from Flow of 0.5 lb/sec through 4 inch Orifice.

Conc. percent	α = 0.05 Plume Diam. ft. 550[a]	α = 0.05 Plume Diam. ft. 150[a]	α = 0.05 Axial Velocity ft/sec 550	α = 0.05 Axial Velocity ft/sec 150	α = 0.05 Height, ft. 550	α = 0.05 Height, ft. 150	α = 0.082 Plume Diam. ft. 550	α = 0.082 Plume Diam. ft. 150	α = 0.082 Axial Velocity ft/sec 550	α = 0.082 Axial Velocity ft/sec 150	α = 0.082 Height, ft. 550	α = 0.082 Height, ft. 150	α = 0.1 Plume Diam. ft. 550	α = 0.1 Plume Diam. ft. 150	α = 0.1 Axial Velocity ft/sec 550	α = 0.1 Axial Velocity ft/sec 150	α = 0.1 Height, ft 550	α = 0.1 Height, ft 150
0.5	49	31	11	7.1	591	439	52	34	9.2	5.8	376	287	54	35.8	8.8	5.4	312	242
1.0	29	20	15	8.3	317	261	30	22	14	7.0	197	168	31	23.0	13	6.5	162	140
1.5	21	16	20	9.4	214	188	21	17	19	8.0	132	119	21	17.4	19	7.6	109	99
2.0	16	13	25	10.5	161	147	16	14	24	9.1	99	92	16	14.1	24	8.7	81	77
2.5	13	11	30	12	129	120	13	12	30	10	79	75	13	11.8	30	10.0	65	62
3.0	11	9.5	36	13	107	101	11	10	35	12	65	63	11	10.1	35	11	54	52
3.5	9.4	8.4	41	14	91	88	9.4	8.7	41	13	56	54	9.5	8.9	41	13	46	45
4.0	8.2	7.5	47	15	80	77	8.3	7.8	47	14	49	48	8.3	7.9	46	14	40	39
4.5	7.3	6.8	53	17	71	69	7.4	7.0	52	16	43	42	7.4	7.1	52	15	35	35
5.0	6.6	6.2	58	18	63	62	6.6	6.4	58	17	39	38	6.6	6.4	58	17	32	31
5.5	6.0	5.7	64	19	57	56	6.0	5.8	64	19	35	34	6.0	5.9	63	18	29	28
6.0	5.5	5.3	69	21	52	51	5.5	5.4	69	20	32	31	5.5	5.4	69	20	26	26
6.5	5.1	4.9	75	22	48	47	5.1	5.0	75	21	29	29	5.1	5.0	75	21	24	24
7.0	4.7	4.6	81	24	44	44	4.8	4.6	81	23	27	27	4.8	4.7	81	23	22	22
7.5	4.4	4.3	87	25	41	41	4.4	4.3	86	24	25	25	4.4	4.4	86	24	21	20
8.0	4.2	4.0	92	26	38	38	4.2	4.1	92	26	23	23	4.2	4.1	92	26	19	19
8.5	3.9	3.8	98	28	36	36	3.9	3.9	98	27	22	22	3.9	3.9	98	27	18	18
9.0	3.7	3.6	104	29	34	33	3.7	3.6	103	29	21	20	3.7	3.7	103	29	17	17
9.5	3.5	3.4	109	31	32	31	3.5	3.5	109	30	19	19	3.5	3.5	109	30	16	16
10.0	3.3	3.3	115	32	30	30	3.3	3.3	115	32	18	18	3.3	3.3	114	32	15	15
15.0	2.2	2.2	172	48	19	19	2.2	2.2	172	47	12	11	2.2	2.2	172	47	9.4	9.4
20	1.7	1.7	229	63	13	13	1.7	1.7	229	63	8.1	8.1	1.6	1.6	229	63	6.6	6.7
25	1.3	1.3	287	78	10	10	1.3	1.3	287	78	6.1	6.1	1.3	1.3	287	78	5.0	5.0

a/ Initial temperature, °R

Table 4. - Characteristics of Hydrogen Plumes from Flow of 100 lbs/sec through 36 inch Orifice.

Conc. percent	α = .05						α = 0.082						α = .1					
	Plume Diam. ft.		Axial Velocity ft/sec		Height, ft.		Plume Diam. ft.		Axial Velocity ft/sec		Height, ft.		Plume Diam. ft.		Axial Velocity ft/sec		Height, ft.	
	550[a]	150[a]	550	150	550	150	550	150	550	150	550	150	550	150	550	150	550	150
0.5	411	261	30	20	5120	3720	445	288	26	17	3270	2440	459	299	24	15	2730	2060
1.0	252	171	40	24	2800	2240	265	187	36	20	1740	1450	270	194	35	18	1440	1210
1.5	181	132	52	27	1910	1630	187	143	48	22	1180	1040	189	148	47	21	971	867
2.0	141	109	64	29	1440	1280	144	117	61	25	886	811	145	121	60	24	728	674
2.5	115	93	77	32	1150	1050	117	100	74	28	708	663	117	102	74	27	581	549
3.0	97	82	90	35	961	894	98	86	88	31	588	559	98	88	87	30	483	462
3.5	84	73	103	57	821	775	85	76	102	34	502	483	88	78	101	33	412	398
4.0	74	65	117	40	716	683	74	68	116	37	437	424	74	69	115	36	359	350
4.5	66	59	131	44	634	609	66	62	129	40	387	377	66	62	129	39	318	311
5.0	59	54	145	47	568	549	60	56	143	44	347	339	60	57	143	43	284	279
5.5	54	50	158	50	514	499	54	52	157	47	314	308	54	52	157	46	257	253
6.0	50	47	172	53	469	457	50	48	171	51	286	282	50	48	171	50	235	232
6.5	46	43	186	57	431	421	46	44	185	54	263	259	46	45	185	54	216	213
7.0	43	41	200	60	398	390	43	41	199	58	243	240	43	42	199	57	199	197
7.5	40	38	214	64	369	363	40	39	213	61	225	223	40	39	213	61	185	183
8.0	37	36	228	67	344	339	37	36	228	65	210	208	37	37	227	64	172	171
8.5	35	34	243	71	322	318	35	34	241	69	197	195	35	35	241	68	161	160
9.0	33	32	256	74	303	299	33	33	256	72	185	183	33	33	256	72	152	151
9.5	31	31	270	78	285	282	32	31	270	76	174	173	32	31	270	76	143	142
10.0	30	29	285	81	270	267	30	29	284	80	165	164	30	30	284	79	135	134
15	20	20	425	118	170	169	20	20	425	117	104	103	20	20	425	117	85	85
20	15	15	567	156	120	120	15	15	566	155	73	73	15	15	566	155	60	60
25	12	12	708	194	90	90	12	12	707	193	55	55	12	12	708	193	45	45

a/ Initial temperature, °R.

Table 5. - Hydrogen Plume Characteristics at Varying Flow Rates - Height of 50 ft, Orifice Diameter of 6 inches.

Flow lbs/sec	Conc.		B		U		Conc.		B		U		Conc.		B		U	
	α = 0.05						α = .082						α = .1					
	550[a]	150[a]	550	150	550	150	550	150	550	150	550	150	550	150	550	150	550	150
.05	7.0	4.2	4.1	3.5	11	6.7	6.0	2.3	6.4	5.5	7.8	4.9	3.3	1.8	7.5	6.6	6.9	4.3
.1	8.2	5.6	4.7	3.8	14	8.3	5.0	3.3	7.1	5.9	10	6.1	4.0	2.5	8.6	7.2	8.7	5.3
.3	9.0	8.0	5.3	4.6	30	12.4	5.6	4.7	8.3	6.7	20	9.2	4.6	3.9	10	8.3	16	7.6
.5	9.0	8.5	5.5	5.0	47	16	5.7	5.3	9.3	7.8	28	11.0	4.8	4.3	10.2	9.1	25	9.5
5	9.0	9.0	5.5	5.5	460	125	5.8	5.8	8.7	8.6	293	80	4.8	4.8	1.5	1.5	240	66

Conc. = percent by volume
B = plume diameter, feet
U = axial velocity, ft/sec

a/ Initial Temperature, °R

Table 6. - Hydrogen Plume Characteristics Function of Orifice Diameter. H_2 Flow of 0.5 lbs/sec., Height of 20 feet

Orifice diameter B_o, inches	Conc.[a]		B[b]		U[c]		Conc.		B		U		Conc.		B		U	
	α = .05						α = .082						α = 0.1					
	550[d]	150[d]	550	150	550	150	550	150	550	150	550	150	550	150	550	150	550	150
4	14.5	14.5	2.3	2.4	166	45	9.3	9.0	3.6	3.6	106	29	7.2	7.5	4.6	4.4	86	24
6	20	20	2.4	2.4	103	3.0	13.3	13.3	3.8	3.7	69	20	11.3	11.3	4.6	4.3	56	16
8	25	24	2.6	2.5	73	22	18	16.7	3.8	3.7	52	16	14	14	4.7	3.3	41	14
12	37	30	2.8	2.7	43	17	23	20	4.1	3.7	32	13	20	17.5	4.8	4.1	28	12
24	-	40	-	2.8	-	16	35	25	4.2	3.4	20	12	30	21.3	4.8	3.8	18	11
36	-	40	-	2.8	-	16	-	26	-	3.3	-	12	35	22.5	5.2	3.8	17	11

a/ Conc = percent by volume.
b/ B = plume diameter, feet.
c/ U = axial velocity, feet/sec.
d/ Initial Temperature, °R.

Hydrogen Explosion Hazards (J. N. Murphy and E. L. Litchfield)

In the event of a large spill of liquid hydrogen, the dimensions of the liquid pool and the rate of liquid evaporation will be influenced by the dimensions of the spill pond and diking. During the existence of the liquid pool, a certain amount of air condensation is to be expected. The amount of such condensate is important as one pound of LH_2 + solid O_2 is equal to two pounds of TNT, and the impulse of this cryogenic mixture is 3 to 5 times that of TNT[11/]. Moderate dilution with nitrogen does not affect either its explosive yield or its impulse significantly.

A 14 x 18 x 5 inch polyethylene tray was used as an evaporator for liquid hydrogen. The sides and bottom of the tray were insulated with 2 inches of foamed urethane. It was pre-cooled with liquid nitrogen. Approximately 1000 grams of LH_2 was placed in the tray and permitted to evaporate in the presence of negligible ambient wind. After about 15 minutes the LH_2 had vaporized, the weight of the condensate was then recorded and a sample was collected for analysis. The gas chromatograph results are shown in table 7.

Table 7. - Vaporization of LH_2 (gas chromatographic analysis)

Trial	Initial Weight of LH_2 (grams)	Weight of Condensate (grams)	Oxygen/Nitrogen of Condensate
1	1080	640	---
2	1270	680	0.70
3	1270	670	0.79
4	1200	577	0.90

Oxygen-nitrogen ratios as high as 0.90 were observed; in all instances the ratio is considerably in excess of the 0.27 ratio for air. The condensate was heavier than anticipated if it is assumed that only the heat of LH_2 vaporization is operative in the condensation process. After LH_2 had vaporized, inspection of the condensate showed only small quantities of water. Thus, even a small pool of LH_2 can condense appreciable quantities of liquid from gaseous air and significant oxygen enrichment occurs within the condensate.

11/ Hydrogen Safety Progress Report No. 5 for the period January 1 to March 31, 1965.

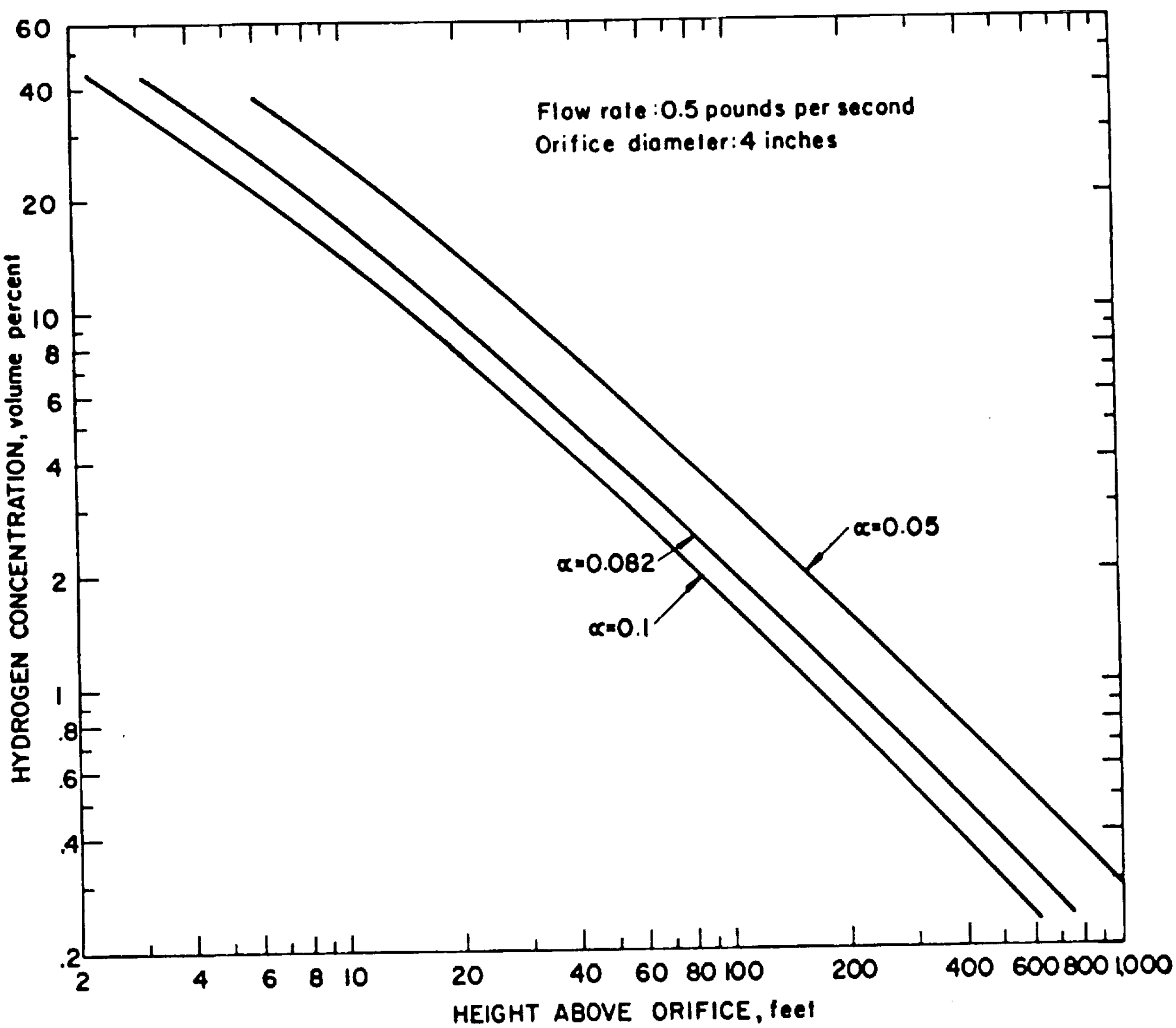

Figure 1. - Prediction of hydrogen concentration at an initial temperature of 550°R above a 4 inch orifice with initial flow of 0.5 lbs/sec.

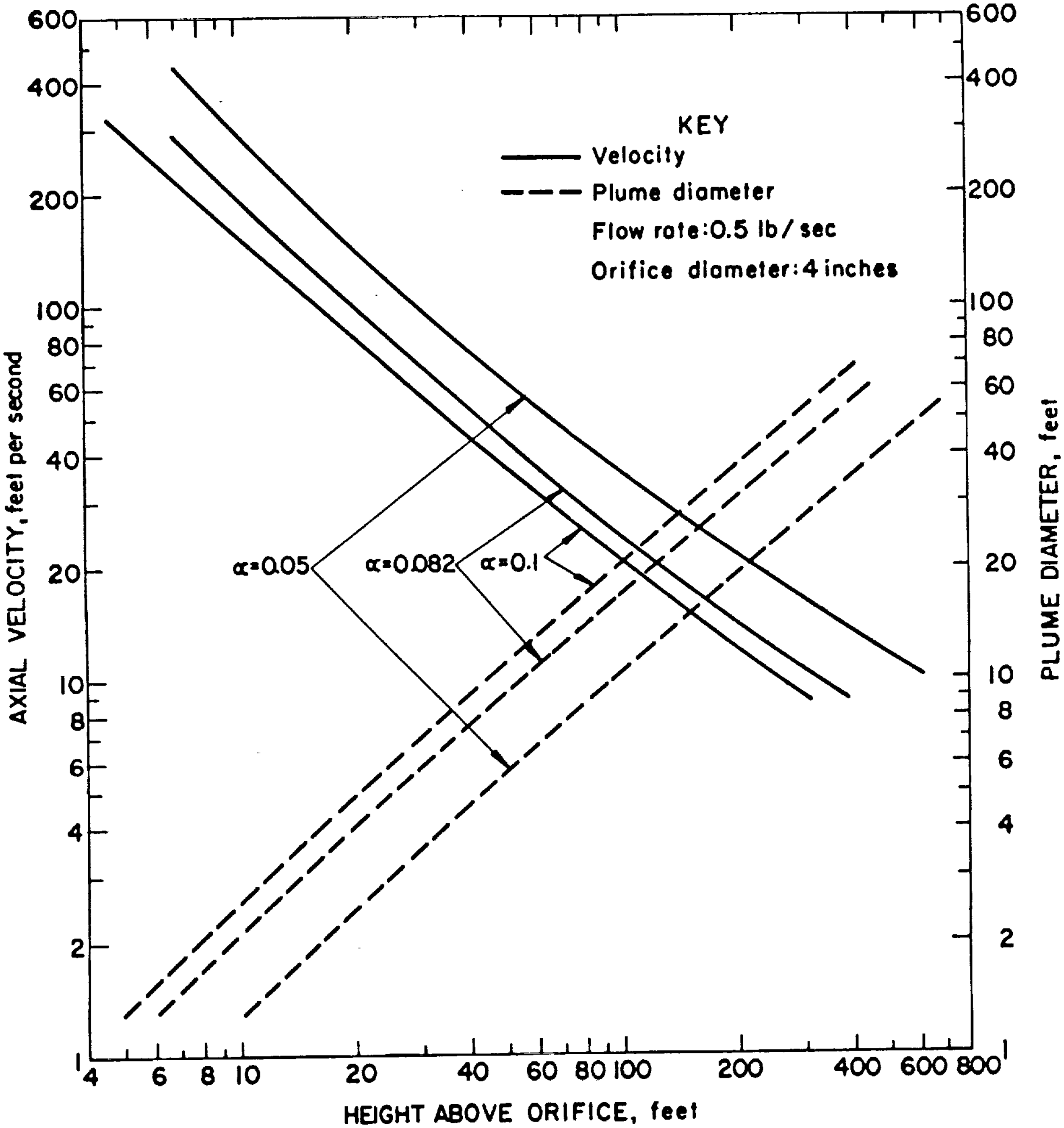

Figure 2. - Prediction of axial velocity and plume diameter above a 4 inch orifice for hydrogen at 550°R with initial flow of 0.5 lbs/sec.

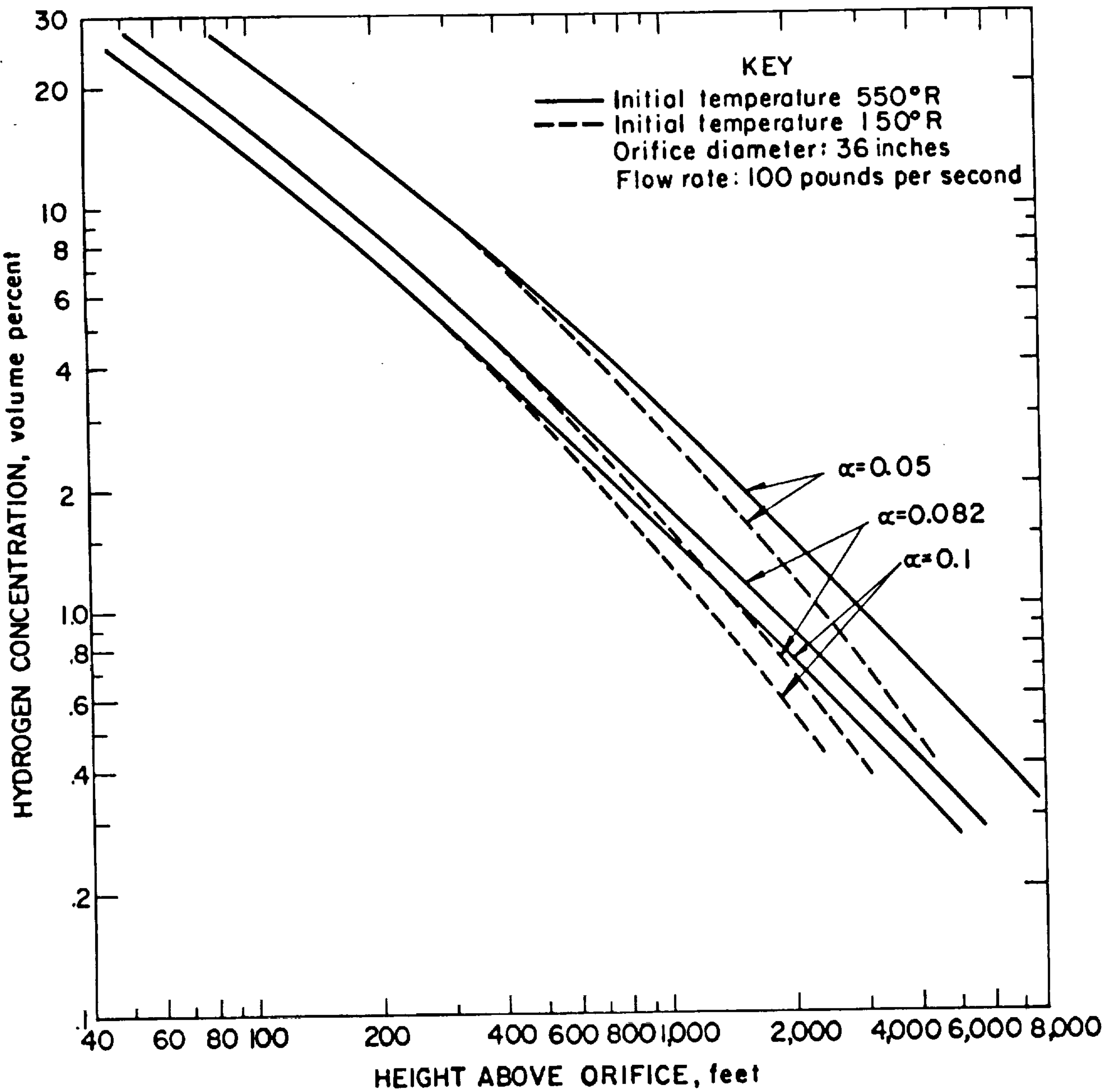

Figure 3. - Prediction of hydrogen concentration above 36 inch orifice with a flow of 100 lbs/sec.

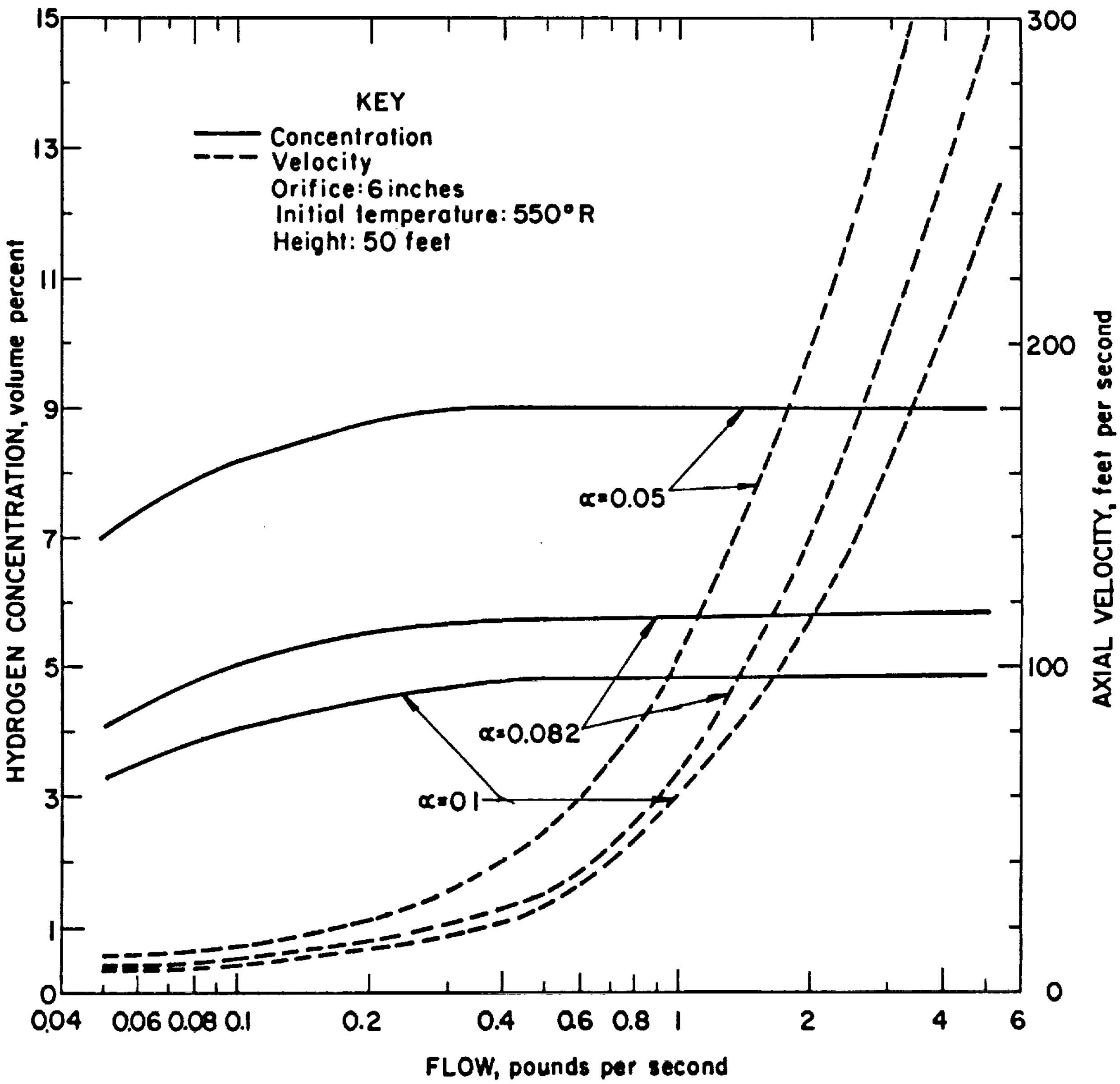

Figure 4. - Hydrogen plume characteristics as a function of flow rate.

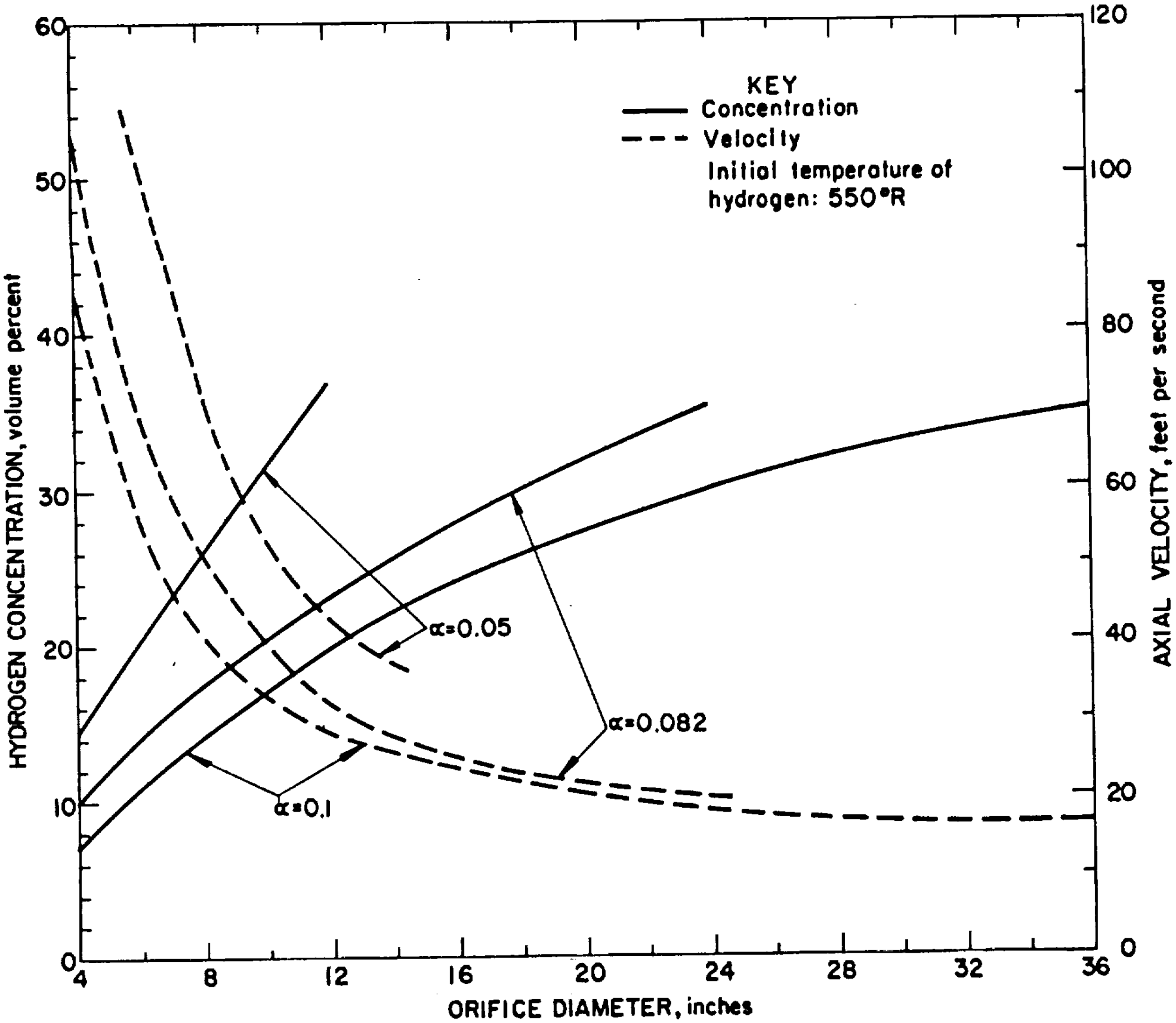

Figure 5. - Effect of orifice diameter on plume characteristics at a height of 20 feet. Initial flow of 0.5 lbs/sec.

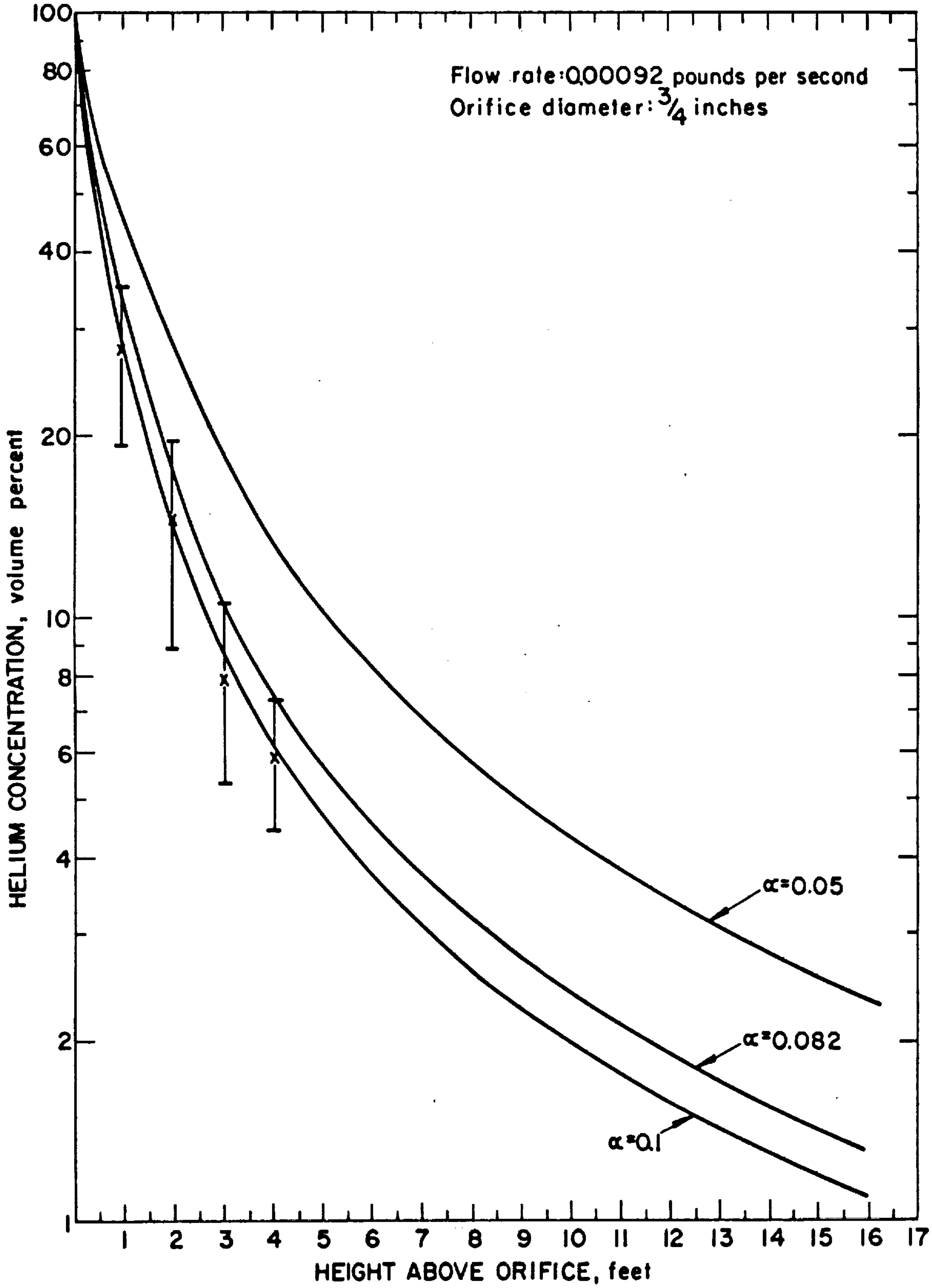

Figure 6. - Predicted and experimental helium concentration as a function of height above 3/4 inch orifice.